

Movement of Pink Shrimp in Relation to the Tortugas Sanctuary

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Abstract.—More than 42,000 adult and juvenile pink shrimp (*Penaeus duorarum*) were tagged and released on the Tortugas (Florida) fishing grounds in 1982–1983 in order to study shrimp movement in relation to the Tortugas sanctuary. For the first time, returns per unit of effort were used in addition to conventional vector analysis to indicate the direction of shrimp movement. Many pink shrimp migrated north and west from the sanctuary to recruit to the fishery. Results supported the historical movement patterns that formed the basis for the establishment of the sanctuary.

There was great interest in pink shrimp (*Penaeus duorarum*) surveys and mark-recapture studies during the late 1950s and early 1960s in the South Florida area (Costello and Allen 1960a, 1961, 1964, 1965, 1966, 1968; Iversen and Idyll 1960; Eldred et al. 1961; Iversen and Jones 1961; Tabb et al. 1962; Idyll et al. 1965; Idyll and Jones 1965; Idyll and Munro 1966; Kutkuhn 1966; Berry 1967). Researchers gathered information on pink shrimp movements, mortality, recruitment, and yield in an attempt to provide fishery managers with the information essential for determining size limits and fishing closures. Their goal then, as now, was to estimate an optimum yield from the fishery.

Initial tagging of pink shrimp in south Florida began in 1957 and provided the first direct evidence of recruitment from Florida Bay to the Tortugas fishing grounds (Iversen and Idyll 1960). Between 1958 and 1963, more than 122,000 shrimp were tagged and released in the upper and middle Florida Keys, Florida Bay, coastal areas of the Everglades, and the Sanibel fishing grounds (Figure 1). Results from these studies indicated that the Tortugas grounds received recruits from all of these areas, although recruitment from the Sanibel grounds appeared minimal (Costello and Allen 1960a, 1961, 1965, 1966; Tabb et al. 1962). Recruitment was continuous throughout the year, although seasonal peaks were observed in spring and fall (Idyll et al. 1965). Florida Bay and adjacent coastal areas of the Everglades became recognized as the major nursery areas for the Tortugas fishery. In studies conducted in Biscayne Bay and Barnes Sound, 40,000 shrimp were marked and released but none were recaptured outside these areas (Costello and Allen 1961, 1966). Tagging experiments also were conducted on the Tortugas grounds (Iversen and Idyll 1960; Iversen and Jones 1961; Costello and Allen 1964, 1966, 1968; Knight 1966;

Berry 1967). Results generally showed large numbers of recoveries within about 16 km of the release sites. Although shrimp moved in all directions, the primary direction was towards the northwest into deeper water.

The Gulf of Mexico Fishery Management Council (GMFMC) provided funds to the National Marine Fisheries Service's (NMFS) Galveston Laboratory of the Southeast Fisheries Center (SEFC) from 1981 to 1983 to conduct several studies to evaluate the effectiveness of the Tortugas sanctuary in preventing the harvest of undersized shrimp (Klima et al. 1986, this issue; Roberts 1986, this issue). Objectives of this study were to determine movements and migration pathways of pink shrimp in relation to the Tortugas sanctuary, an area closed to trawling by the State of Florida and the federal government (GMFMC 1980; Klima and Costello 1982). The specific questions addressed were: Do present patterns of pink shrimp movement differ from those delineated by earlier investigators? Do pink shrimp leave the sanctuary? If so, do they migrate north and west to trawlable areas or do they travel south into predominantly untrawlable reef areas?

In this description of the first major shrimp tagging experiments conducted on the Tortugas fishery since 1965, a new index—returns per unit effort (R/f)—is used in addition to conventional vector analysis to indicate direction of movement. Use of this index reduces bias in the number of tag returns reported from different geographic areas of the fishing grounds when fishing effort is nonuniformly distributed.

Methods

Collecting and tagging operations were conducted from the *Miss Virginia*, a 23-m-long commercial shrimp boat. Pink shrimp were collected

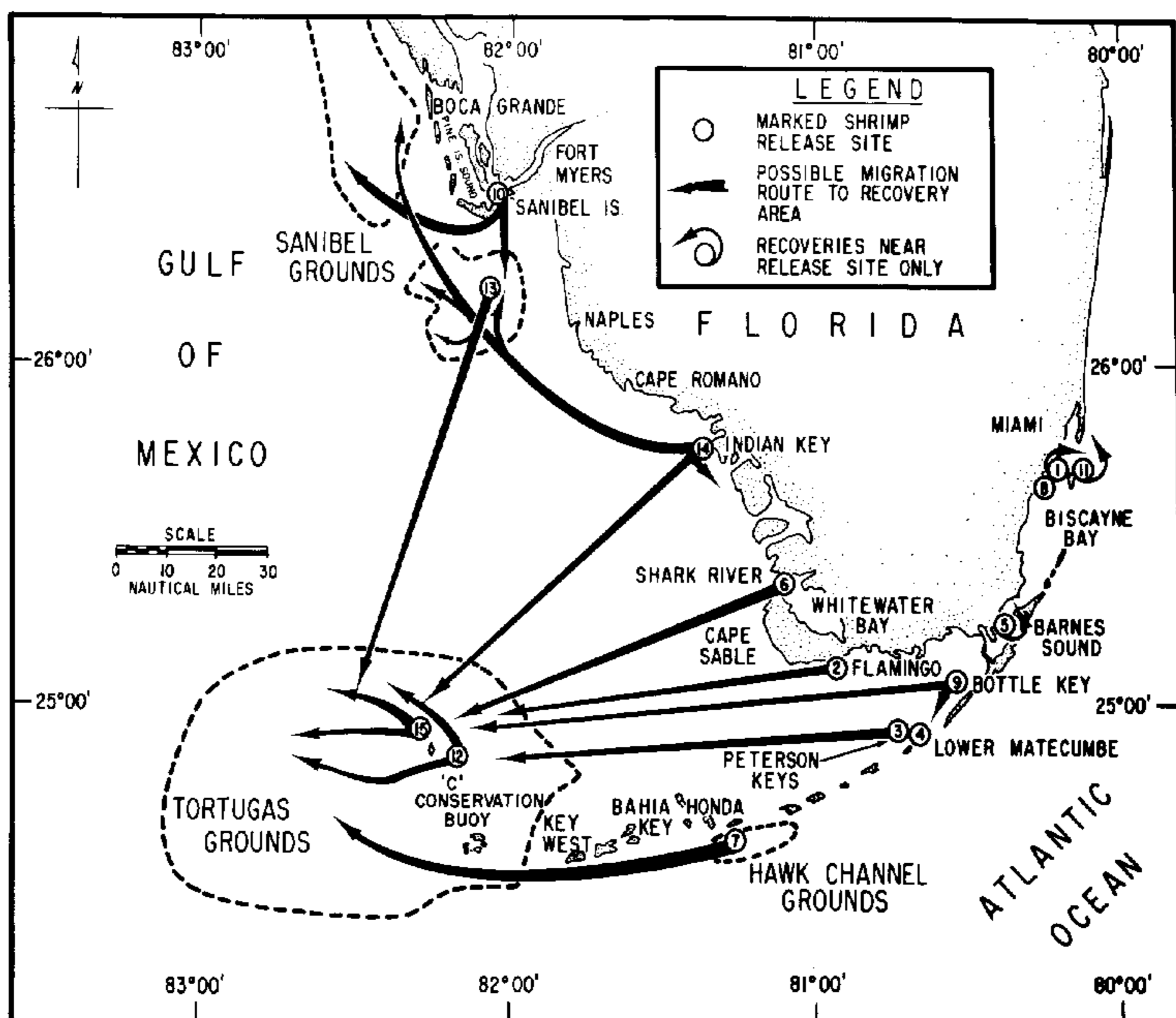


FIGURE 1.—Sites at which marked pink shrimp were released and recovered in south Florida waters, 1958–1963 (from Costello and Allen 1966).

nightly in 5–15-min tows with two double-rigged, 12-m otter trawls. After tow completion, nets were emptied on deck and small (<50 mm in rostrum-telson length) and moribund shrimp were discarded. Remaining shrimp were placed in temporary holding tanks. One 2.3-kg sample of shrimp was collected each night, frozen, and returned to the NMFS Galveston Laboratory for length and sex determinations. Length measurements were not recorded for those individual shrimp that were tagged in the manner described by Marullo et al. (1976). Measured samples thus were representative of the population of shrimp tagged each night rather than the total catch. Each tagged shrimp was transferred immediately to a plastic release canister placed inside a 45-L ice chest containing continuously aerated seawater. After approximately 75 shrimp were tagged, the canister was sealed, weighted, and released over the side of the vessel. Each expendable canister was designed to reduce immediate predation on tagged shrimp; a

device on each delayed the canister's opening for 5–15 min after deployment (Emiliani 1971).

More than 42,000 adult and juvenile pink shrimp were marked and released over a 5-month period at different locations on the Tortugas grounds to determine movement and migration patterns. Approximately 10,000 pink shrimp were tagged each month in November 1982 and in January, February, and March 1983. Shrimp were released in four general areas of the Tortugas fishing grounds: inside the sanctuary, 4–19 km north of the sanctuary, 6–19 km north of Rebecca Shoal, and about 28 km south of Rebecca Shoal (Figure 2). Temporal and spatial considerations required that the results be analyzed in terms of 11 separate shrimp releases, each area and month of release representing a separate experiment.

Publicity posters describing both the study and a lottery award system were prominently displayed at area fish houses to encourage cooperation from commercial fishermen. Individuals who

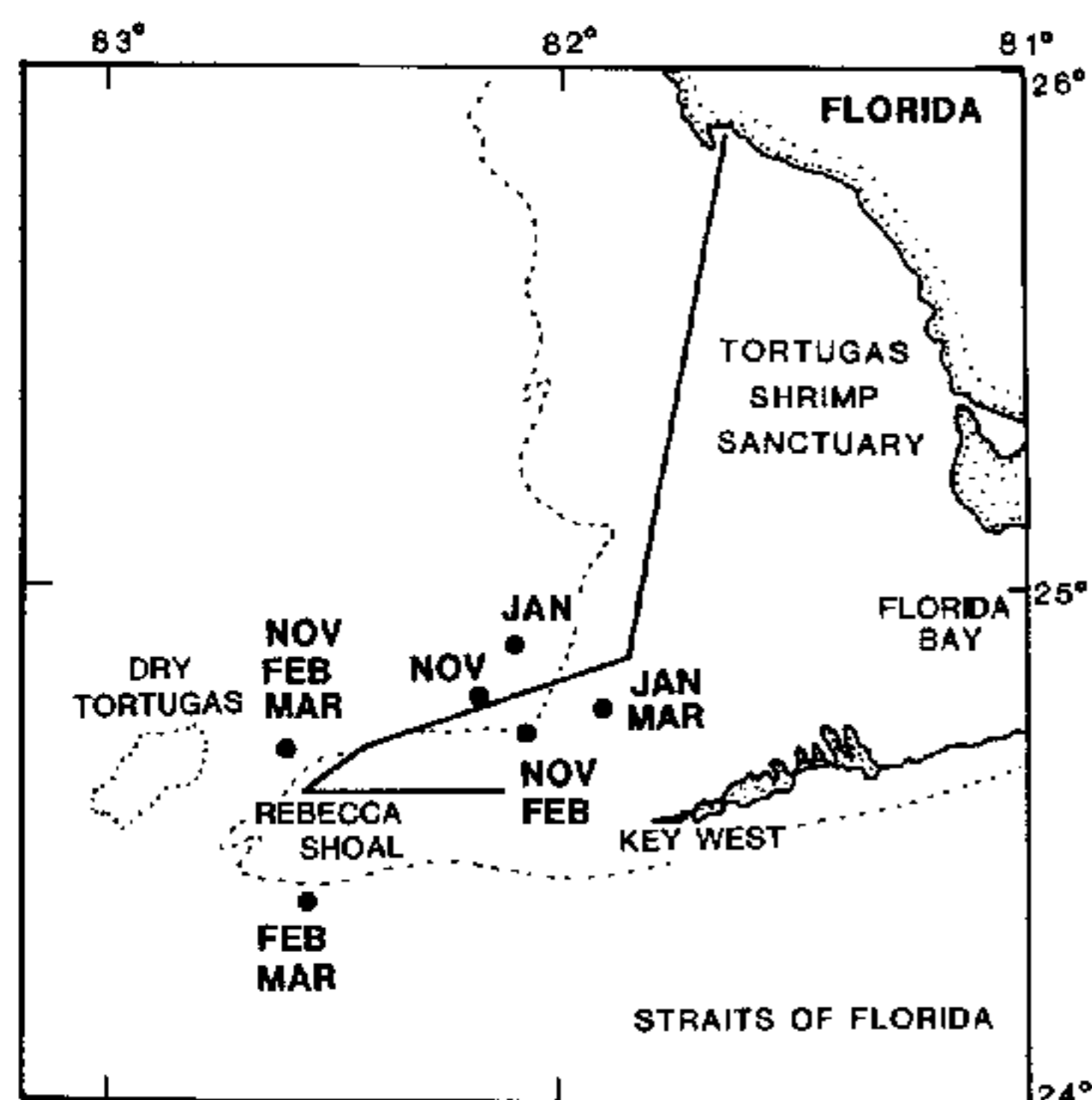


FIGURE 2.—Release sites and dates (November 1982, January–March 1983) of tagged pink shrimp in and around the Tortugas shrimp sanctuary (marked by a solid line). The 10-fathom contour is shown by a dashed line.

returned tagged shrimp with information on the date and location of recapture became eligible for monthly drawings that featured one \$500, one \$100, and six \$50 prizes.

Port agents employed by the SEFC Fishery Information Management Division (FIMD) interviewed commercial shrimpers and shrimp dealers to obtain detailed information about returned tagged shrimp and fishing effort. Three NMFS observers were placed opportunistically aboard commercial shrimp vessels to collect supplementary recapture data. Every attempt was made to collect information from each shrimp vessel that docked in the Key West area. Fishing effort data were obtained for 3,196 vessel trips from November 15, 1982, through May 31, 1983 (shrimp landing data from the National Oceanic and Atmospheric Administration [NOAA] Environmental Data and Information Service, 1982 and 1983). This number was used as a reasonable approximation of total fishing effort on the Tortugas grounds. (In a personal communication, Edward Little of FIMD in Key West estimated that 99% of all vessel trips were included in the survey.)

Pink shrimp returns were checked for accuracy and, when necessary, interviews were repeated. Trip records for many vessels were incomplete. All records gave the weight of landed shrimp as well as the date of landing, date of the interview or both. About 44% of the records also included dates of the fishing trip and data on the fishing effort expended. About 1,300 records gave accu-

rate fishing locations in addition to the dates and duration of trips.

Two methods were used to evaluate the data for direction of shrimp movement: shrimp returns per unit of fishing effort (number of returns per 24-h day); and resultant vector analysis. The first method depended on detailed fishing effort data and allowed adjustment for geographic variations in effort; the second assumed fishing effort was constant both in space and time.

Determination of returns per unit of effort.—The spatial and temporal distribution of fishing effort was quantified to describe pink shrimp movement over time. To accomplish this, a NOAA chart 11434 of the Tortugas grounds was subdivided into several geographic areas and the amount of fishing effort in each area was determined for specific time periods. The number of shrimp returns per unit of effort was then calculated for each division of space and time.

The 3,196 trips were sorted chronologically into 13 groups representing different time periods throughout the study. I arbitrarily selected approximate biweekly time periods of calendar days 1–15 and day 16 to the end of the month for each sampling month. Average fishing effort (number of 24-h days) per trip was calculated for each biweekly period from the nearly 1,400 trip records that included effort data. This value was multiplied by the total number of trips in each time period to obtain 13 estimates of total biweekly effort (f_i). The location of each fishing trip together with its corresponding fishing effort was plotted on a chart of the Tortugas grounds for each biweekly period. Forty-one percent of the trip records contained the data necessary to prepare these 13 charts. The charts of the fishing grounds were then subdivided into 16 grids (Figure 3). Trawl locations often were reported in general terms rather than in precise coordinates so that it was impossible to partition the Tortugas area into small grids of equal size. Consequently, large grids of unequal size were defined that reflected the trawling locations described in the interviews. For each of the 13 time periods, the amount of fishing effort within each grid was summed. The ratio of effort per grid to sum of effort for all grids ($f_g/\Sigma f_g$) was calculated from chart data and multiplied by total biweekly effort (f_i) to determine total effort per grid (Table 1).

The number of validated shrimp returns (recapture date accurate within 3 d) from each grid and time period was determined separately for the 11 release experiments (Table 2). The correspond-

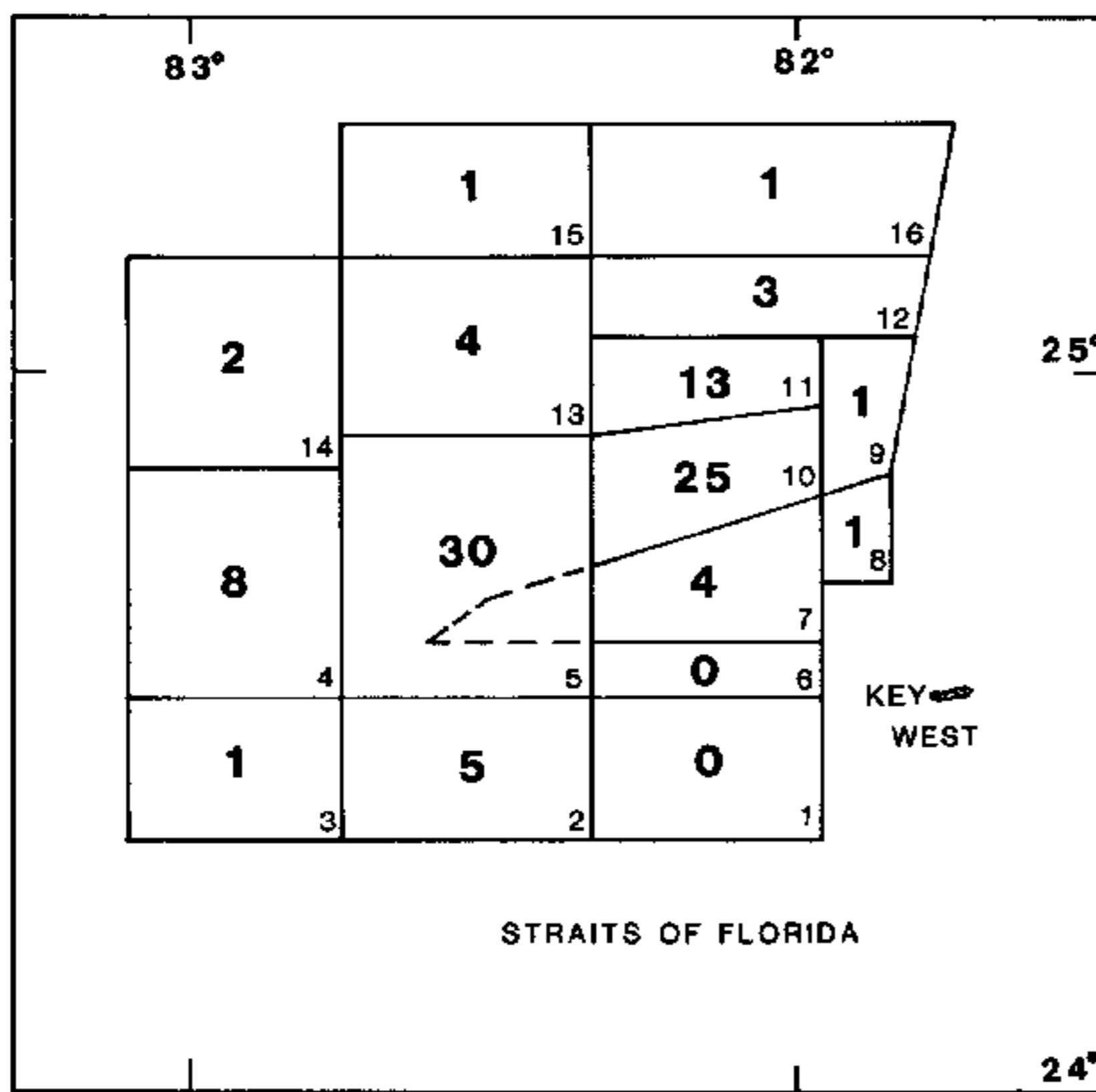


FIGURE 3.—Percentages (large numbers) of total fishing effort (24-h days) for shrimp in 16 grid areas (small numbers) on the Tortugas fishing grounds from November 15, 1982, through May 31, 1983.

ing values of returns/24 h of fishing effort (R/f) were then calculated. A summary of these results was prepared for each experiment by adding R/f values for a given grid across all time periods. This provided an indication of the number of shrimp returned from every grid as a function of the fishing effort required for recapture. The general direction of shrimp movement was obtained by determining compass headings from the release grid

to grids with the highest R/f values. These values were not computed for periods in which biweekly effort in a given grid (f_g) was less than 10 d. A low level of trawling activity, analogous to small sample size, was considered unreliable because a single, chance shrimp recapture in such a grid would yield a grossly inflated R/f value.

Resultant vector analysis.—The direction of the resultant vector from release to recapture location was determined to provide a comparison with the results from the returns-per-effort analysis. I arbitrarily decided to include only pink shrimp traveling a minimum of 9 km (Iversen and Idyll 1960) because minor errors in recapture locations can create major errors in resultant vector calculations for short movements. Based on the direction of travel, the percentage of returns recovered in each of the eight octants of the compass (north, northeast, east, etc.) was determined. This analysis was independent of the grid system and therefore could not be adjusted for geographic variations in fishing effort. If fishing effort was not uniform at each compass direction from the release site, then conclusions based on resultant vector analysis could be inaccurate.

When results obtained by R/f analysis are compared with those from resultant vector analysis, it is important to note that each procedure utilized different but overlapping data sets. The former method used returns (with accurate recapture dates and locations) taken outside the release grid. The latter used returns (with accurate recapture loca-

TABLE 1.—Total trawling effort (number of 24-h days) for pink shrimp by fishermen on the Tortugas fishing grounds, calculated by grid and month, 1982–1983. A represents calendar days 1–15 of each month; B represents day 16 through the end of each month.

Grid	Nov	Dec		Jan		Feb		Mar		Apr		May		Total
	B	A	B	A	B	A	B	A	B	A	B	A	B	
1	0	1	5	0	0	10	4	2	0	5	3	1	0	31
2	0	6	19	28	40	7	50	20	69	121	136	31	77	604
3	4	4	0	9	0	7	33	8	12	4	33	2	24	140
4	56	71	60	63	42	44	117	42	213	52	82	3	28	873
5	192	170	173	191	332	101	376	260	381	375	307	183	319	3,360
6	0	0	0	0	5	0	0	0	0	0	0	0	0	5
7	14	46	7	26	44	50	51	63	42	36	26	13	7	425
8	0	8	0	1	3	9	3	4	0	13	45	0	0	86
9	10	0	13	1	10	0	3	4	57	3	11	4	4	120
10	136	189	188	325	232	224	234	145	274	189	184	217	195	2,732
11	128	120	90	111	176	243	85	81	90	116	80	49	72	1,441
12	36	10	16	38	37	32	48	27	39	21	13	24	9	350
13	0	75	57	19	42	29	70	15	53	27	50	19	16	472
14	0	13	7	1	28	1	34	7	67	15	47	10	14	244
15	0	0	0	0	27	0	34	8	18	0	0	18	4	109
16	0	0	0	0	10	8	4	0	0	15	0	29	55	121
Total	576	713	635	813	1,028	765	1,146	686	1,315	992	1,017	603	824	11,113

TABLE 2.—Release and recapture summary for tagged pink shrimp by month and area on the Tortugas fishing grounds, 1982–1983.

Year, month (location of release ^a)	Number released	Number recaptured ^b	Percent recaptured ^b	Number of validated returns ^c	Number of recaptures by distance traveled ^d	
					≥ 9 km	< 9 km
1982						
Nov (S)	7,743	493	6	349	302	73
Nov (N)	2,190	407	19	291	93	229
Nov (W)	2,288	273	12	207	67	168
1983						
Jan (S)	6,682	704	11	449	363	284
Jan (N)	3,295	798	24	697	214	487
Feb (S)	5,571	891	16	401	297	278
Feb (W)	3,389	722	21	589	201	431
Feb (SS)	995	186	19	132	27	109
Mar (S)	5,891	458	8	344	161	266
Mar (W)	1,787	309	17	172	37	224
Mar (SS)	2,298	351	15	322	17	310
Total	42,129	5,592	13	3,953	1,779	2,859

^a S = sanctuary; N = north of sanctuary; W = west of sanctuary; SS = south of sanctuary.

^b Through October 31, 1983; other data columns refer to recaptures through May 31, 1983.

^c Includes data with recapture locations and known recapture dates (accurate within ±3 d).

^d Includes data with recapture locations regardless of recapture dates.

tions regardless of recapture date) taken at least 9 km from the actual release site. Consequently, pink shrimp recaptured inside the release grid after traveling 9 km appeared to be immobile in the *R/f* analysis but displayed directional movement in the resultant vector analysis. The opposite was true for shrimp taken outside the release grid but still within 9 km of the release site. In general, most returns used in the resultant vector analysis were obtained within the release grid.

Results

Return Rate and Minimum Distance Traveled

Over the 11 experiments, 42,129 tagged pink shrimp were released and 5,592 were returned through October 1983, for an overall return rate of 13%. The January release north of the sanctuary had the highest percentage of returns (24%), and the November release inside the sanctuary had the lowest (6%).

The minimum distances traveled by tagged shrimp were determined from release and recapture locations and assumed straight-line movements. Actual distances traveled were not calculated because deviations from linear movement could not be tracked. Sixty-two percent of all pink shrimp returns were taken within 9 km of the release sites, 83% were within 18 km, and 91% were within 27 km (Figure 4). The minimum distance traveled by recaptured shrimp ranged from 0 to 157 km. In general, shrimp released south of the

sanctuary were recaptured closer to the release site than those released to the north and west (Table 3). Ninety-five percent of shrimp returned from the March release south of the sanctuary migrated a straight-line distance less than 9 km, whereas only 20% of those recovered from the November sanctuary release had moved this little. As a group, shrimp released inside the sanctuary traveled farthest (Table 4).

Time at Large

Over 49% of all returned pink shrimp were recaptured within 20 d of release, 76% within 30 d, and 93% within 60 d (Table 5). Time at large ranged from 1 to 171 d and was similar for shrimp released within the sanctuary and to the north and

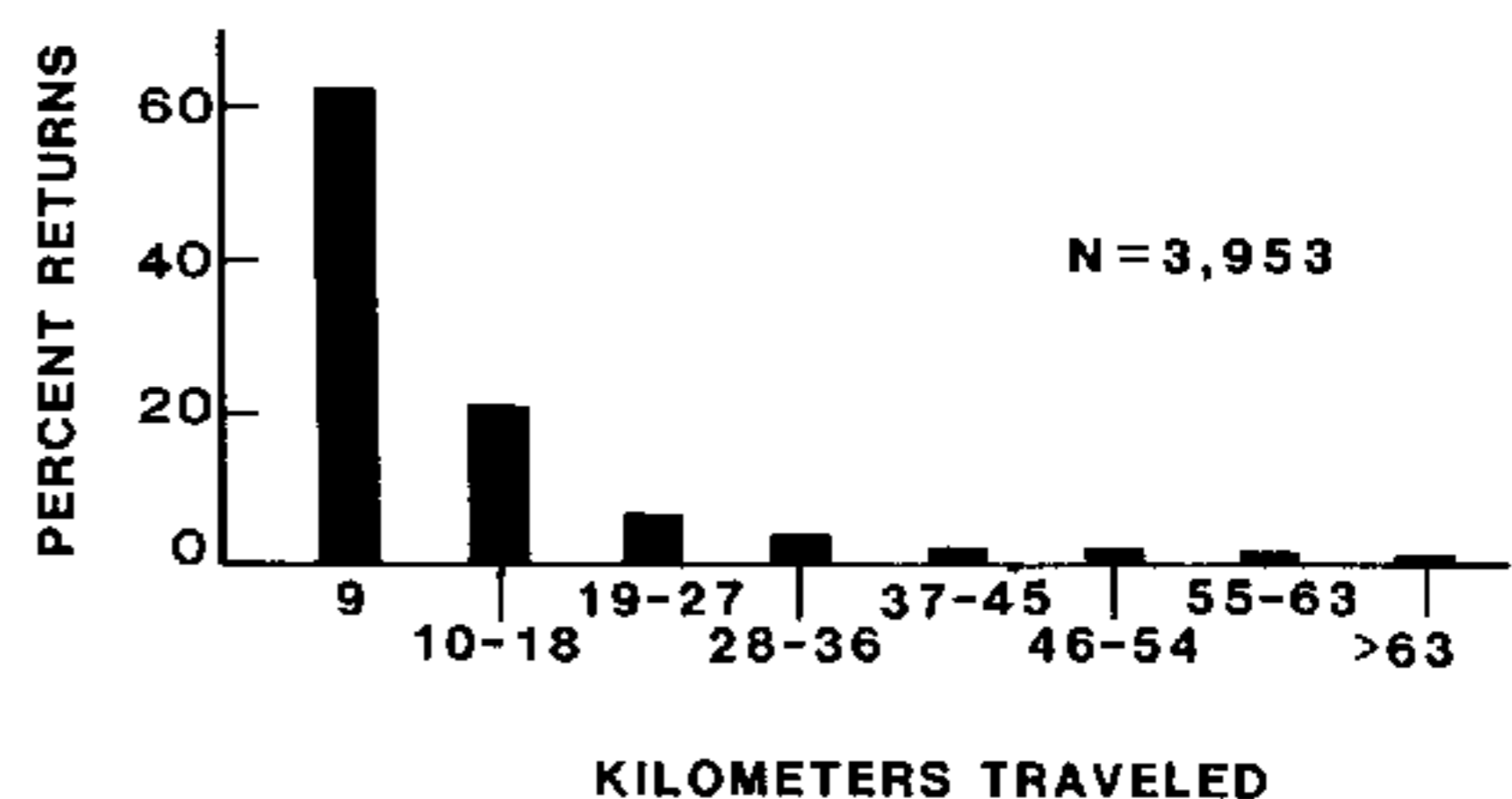


FIGURE 4.—Distribution of straight-line distances traveled by tagged and recaptured pink shrimp (all release sites combined) on the Tortugas fishing grounds, 1982–1983.

TABLE 3.—Cumulative percentage of returns of tagged pink shrimp, by kilometers traveled, for each release site and date of release, 1982–1983.

Month and location of release ^a	Kilometers traveled								Number of returns
	0–9	10–18	19–27	28–36	37–45	46–54	55–63	>63	
Nov S	19.5	66.7	87.7	92.8	98.4	98.4	98.7	100	375
Jan S	43.9	69.9	81.3	92.1	96.0	96.6	99.4	100	647
Feb S	48.4	69.7	83.1	90.3	93.9	98.1	93.3	100	575
Mar S	62.3	94.9	97.2	97.9	99.1	99.3	99.8	100	427
Nov N	71.1	92.2	94.7	97.5	98.5	99.1	100		322
Jan N	69.3	87.5	92.0	94.6	97.6	98.4	99.0	100	701
Nov W	71.5	84.7	91.1	97.4	97.9	100			235
Feb W	68.0	82.4	93.0	96.2	97.2	98.4	100		632
Mar W	85.8	93.9	96.2	99.6	100				261
Feb SS	80.2	91.9	94.1	100					136
Mar SS	94.8	98.2	99.7	100					327
All	61.6	82.6	90.7	95.3	97.5	98.6	99.6	100	
Number of returns	2,857	972	376	213	104	50	45	21	4,638

^a S = sanctuary; N = north of sanctuary; W = west of sanctuary; SS = south of sanctuary.

west of it. At least six shrimp released in the sanctuary were recaptured there more than 3 months later.

Time at large for pink shrimp recaptured within 9 km of the release site also was determined. For all experiments combined, 83% of these shrimp were taken within 30 d of release, 14% within 30–60 d, and 3% after 60 d (Table 5). Data were similar for all release areas.

Size

Paired *t*-tests were used to analyze the percentages of recaptured pink shrimp having a total length less than 103 mm (69 tails/lb). For shrimp tagged within the sanctuary, there was no significant difference ($P > 0.05$) in the proportion of these small shrimp between animals recaptured inside the sanctuary and outside it (Table 6). Samples collected nightly during tagging operations within the sanctuary had significantly higher ($P < 0.05$) percentages of shrimp shorter than 103 mm than either of the aforementioned recapture groups.

TABLE 4.—Numbers of tagged pink shrimp recaptured within 9 km of release sites on the Tortugas grounds and corresponding percentages of all recaptures originating in the respective areas, 1982–1983.

Release area	Number recaptured	Percent of all recaptures
Sanctuary	718	49
North of sanctuary	686	69
West of sanctuary	670	69
South of sanctuary	419	92

Migration

Sanctuary releases.—In all four sanctuary experiments, the highest return-per-effort values (other than for release grids) were obtained from grids lying to the north, northwest, and west of the release site, indicating pink shrimp movement was primarily in those directions (Figure 5). Only 4 of 1,543 returns were recovered south of the sanctuary in grids 1 and 2. Five shrimp released in grid 7 in November traveled more than 63 km and were recaptured to the north and northwest of grids 15 and 16.

Resultant vector analyses (uncorrected for variations in fishing effort) for all sanctuary experiments combined (Table 7) indicated movement to

TABLE 5.—Times at large for tagged pink shrimp released and recaptured on the Tortugas grounds, 1982–1983. Data are numbers and percentages (in parentheses) of recaptured shrimp by release area.

Release area	Days at large		
	0–30	31–60	>60
All recaptured pink shrimp			
Sanctuary	1,158 (75)	249 (16)	136 (9)
North of sanctuary	794 (80)	157 (16)	37 (4)
West of sanctuary	684 (71)	198 (20)	86 (9)
South of sanctuary	390 (86)	63 (14)	1 (<1)
Total	3,026 (76)	667 (17)	260 (7)
Pink shrimp recaptured within 9 km of release site			
Sanctuary	590 (82)	106 (15)	22 (3)
North of sanctuary	603 (88)	73 (11)	10 (1)
West of sanctuary	496 (74)	129 (19)	45 (7)
South of sanctuary	368 (88)	51 (12)	0 (0)
Total	2,057 (83)	359 (14)	77 (3)

TABLE 6.—Numbers and percentages (in parentheses) of pink shrimp in two total-length categories for samples collected nightly during sanctuary tagging operations and for shrimp subsequently recaptured inside or outside the sanctuary, Tortugas grounds, 1982–1983.

Month of release	Recaptures inside sanctuary		Recaptures outside sanctuary		Nightly samples	
	<103 mm	≥103 mm	<103 mm	≥103 mm	<103 mm	≥103 mm
Nov	5 (8)	55 (92)	20 (10)	172 (90)	519 (72)	198 (28)
Jan	102 (19)	443 (81)	6 (8)	70 (92)	313 (38)	516 (62)
Feb	72 (26)	208 (74)	47 (18)	221 (82)	241 (54)	207 (46)
Mar	151 (51)	144 (49)	48 (41)	69 (59)	584 (77)	172 (23)
Total	330 (28)	850 (72)	121 (19)	532 (81)	1,657 (60)	1,093 (40)

the west (66%), northwest (18%), and north (8%). These directions were similar to those obtained by the return-per-effort analysis. The mean straight-line distances traveled were 24, 20, and 20 km, respectively, to the west, northwest, and north.

Releases north of the sanctuary.—In the November release north of the sanctuary, pink shrimp migrated from grid 10 to grids 11 ($R/f=0.17$) and 5 ($R/f=0.07$) to the north and west-southwest (Figure 6). In the January experiment, movements from release grids 10 and 11 were to the northwest away from the sanctuary (grid 13, $R/f=0.31$) and to the south into the sanctuary (grid 7, $R/f=0.31$).

Movements into grids 12 ($R/f=0.18$) and 5 ($R/f=0.10$) also were noted. There was one report of a pink shrimp recaptured 157 km to the north-northwest. Three of 987 returns came from south of the sanctuary in grids 1 and 2.

Resultant vector analyses indicated a somewhat different trend than that found in the return-per-effort analyses (Table 7). For the combined November and January experiments, movement was to the west (28%), southwest (27%), and south (16%), and mean distances traveled at these headings were 22, 28, and 13 km, respectively.

Releases west of the sanctuary.—In the November experiment west of the sanctuary, most movement (Figure 6) from release grid 5 was to the north (grid 13, $R/f=0.13$) and west (grid 4, $R/f=0.11$). The February experiment showed migration from the same grid into grids 4 ($R/f=0.17$), 2 ($R/f=0.16$), and 11 ($R/f=0.11$) to the west, south, and northeast, respectively. Movement from grid 5 southward into grid 2 ($R/f=0.06$) and westward into grid 4 ($R/f=0.02$) predominated in the March experiment. However, only 11 of 172 returns were reported from outside the March release grid, compared with 27 of 207 for November and 58 of 576 for February. Three of the 7,464 shrimp released at this site were returned from inside the sanctuary. Resultant vector analyses (Table 7) of all three releases combined showed that shrimp traveled to the northeast (37%), northwest (19%), and east (15%) with mean distances of 20, 19, and 31 km, respectively.

Releases south of the sanctuary.—Only nine of 454 shrimp returns were reported to have emigrated from the southern release grid 2. Eight returns ($R/f=0.02$) from the February release and one ($R/f=0.00$) from the March release came from grid 5 to the north (Figure 5). Resultant vector analyses indicated movement was to the west (50%), north (20%), and east (16%) with mean distances of 15, 31, and 11 km, respectively (Table 7).

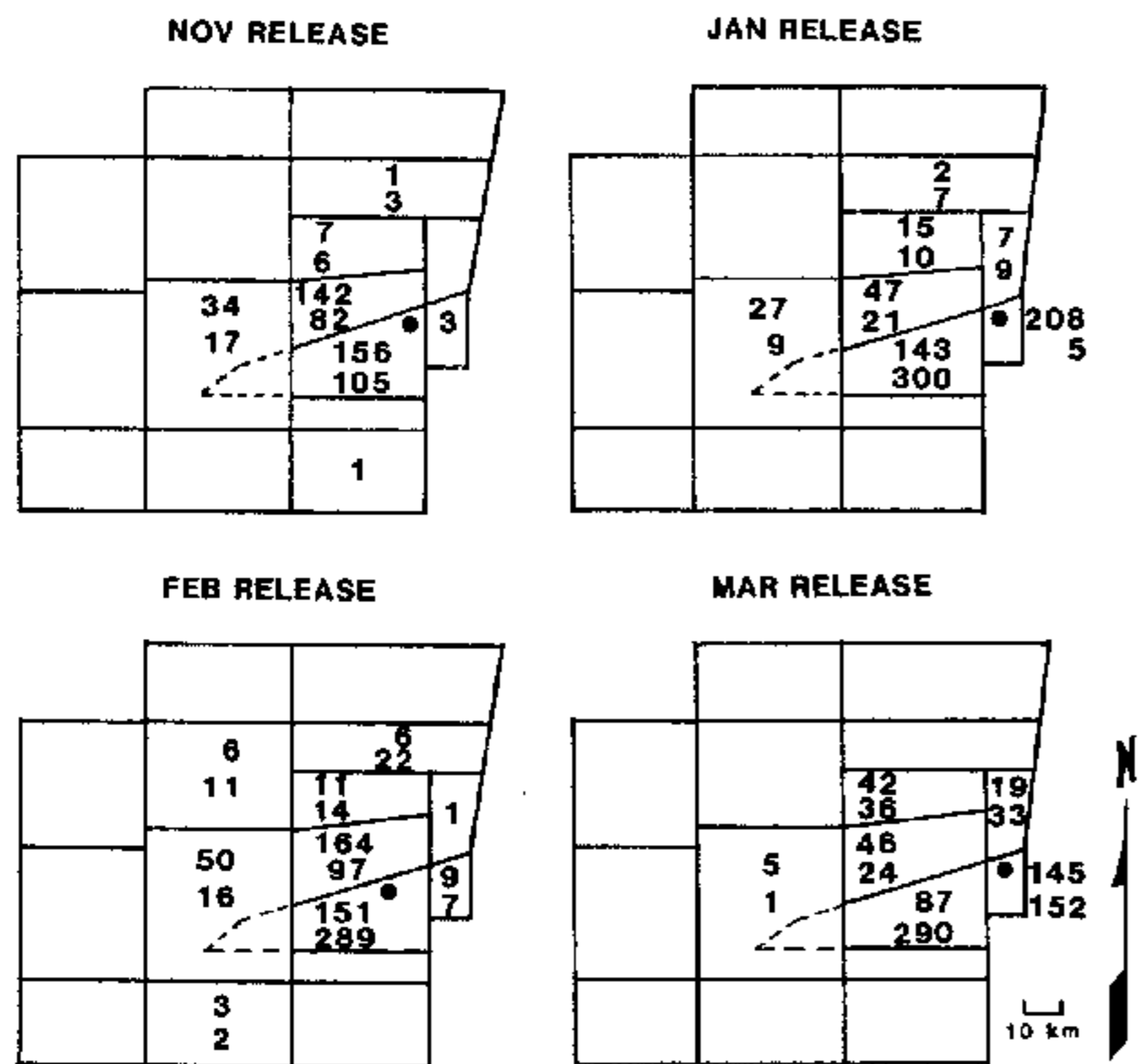


FIGURE 5.—Numbers of tagged pink shrimp returned (top number in each grid) and numbers returned per unit fishing effort (bottom number: $10^2 \times$ returns per 24-h day) from release sites within the Tortugas sanctuary, 1982–1983. Values represent sums of biweekly calculations from the beginning of experiments through May 31, 1983. Values for returns per unit effort were not summed when effort reported from interviews was less than 10 d/grid. Black circles represent release locations for tagged shrimp. See Figure 2 for identification of grids.

TABLE 7.—Resultant vector analyses of pink shrimp movement from each release area, Tortugas grounds, 1982–1983. Percentages of returns at each compass heading and mean kilometers traveled (in parentheses) are shown. Only shrimp traveling at least 9 km are included.

Release area	Direction of movement							
	N	NE	E	SE	S	SW	W	NW
Sanctuary	8 (20)	2 (13)	2 (11)			4 (17)	66 (24)	18 (20)
North of sanctuary	7 (19)	6 (17)	7 (17)	2 (15)	16 (13)	27 (28)	28 (22)	7 (26)
West of sanctuary	7 (19)	37 (20)	15 (31)	3 (35)	7 (30)	2 (22)	10 (17)	19 (19)
South of sanctuary	20 (31)	14 (13)	16 (11)				50 (15)	

Discussion

The life cycle of the pink shrimp begins with offshore spawning by adults. Larvae develop as they move shoreward and metamorphose into postlarvae prior to reaching the bays and estuaries that serve as nursery grounds. In Florida Bay, from 2 to at least 6 months pass before subadults migrate from the bay westward to the Tortugas fishing grounds (Costello and Allen 1966).

Pink shrimp were tagged during seasonal peaks in commercial fishing effort and shrimp movement from Florida Bay. The high return rate (13%) in this study lends strength to the analyses reported herein.

Most pink shrimp were recaptured less than 9 km from the release site and were at large less than 30 d. Similar results were obtained by earlier investigators. Iversen and Jones (1961), Costello and Allen (1964), and Berry (1967) found that pink shrimp generally were recaptured within about 9–18 km of the release site; the percentages of pink shrimp recaptured within 20, 30, and 60 d at large were 68, 81, and 94%, respectively (Iversen and Jones 1961). These are comparable to the results shown here (Table 5).

Return-per-effort values and resultant vector analyses clearly indicated that pink shrimp from the Tortugas sanctuary recruited to the open fishing grounds to the north and west, which supports earlier findings (Iversen and Idyll 1960; Costello and Allen 1960a, 1961, 1965, 1966, 1968; Iversen and Jones 1961; Tabb et al. 1962; Knight 1966). Although seasonal variations in shrimp movement on the Tortugas grounds are not well documented, studies conducted during September–December 1961 and December 1962–March 1963 showed similar net movement to the northwest (Costello and Allen 1966). Westward movement of juvenile pink shrimp from Florida Bay to the

Tortugas grounds has been well documented (Costello and Allen 1960a, 1960b, 1964, 1966; Iversen and Idyll 1960; Tabb et al. 1962). Eastward movement toward Florida Bay was neither expected nor observed. However, data were limited because no fishing activity was reported east of grid 8. It could not be determined if shrimp released in the sanctuary moved south into untrawlable shoal areas extending from Key West to Rebecca Shoal. However, if considerable southward migration from the sanctuary did occur, many returns would be expected from grids 1 and 2. Commercial trawling in grid 2 provided three returns while grid 1 had a very low level of effort and provided only one return. These shrimp may have followed any of three migratory routes: south across the reef, south through navigable channels in the reef, or west to Rebecca Shoal and then south, circumventing the reef.

There also was little movement of tagged pink shrimp into the sanctuary from the open fishing grounds, although large numbers of shrimp recruited to the open grounds from the sanctuary. Of the 16,242 shrimp released outside the sanctuary, only 29 of the 2,439 returns were taken in the sanctuary. Of the 25,887 shrimp released inside the sanctuary, 902 were recaptured there and 636 were recaptured outside. Non-reporting or false reporting of tag recaptures by fishermen poaching inside the sanctuary may have affected these values. However, NMFS observers validated many of the recapture locations reported by illegal fishermen, and the data strongly supported the concept of net shrimp movement out of the sanctuary.

Movement from sites north and west of the sanctuary was variable. At least low levels of pink shrimp movement occurred between all release grids with one exception: shrimp were not found to migrate from the southernmost release site

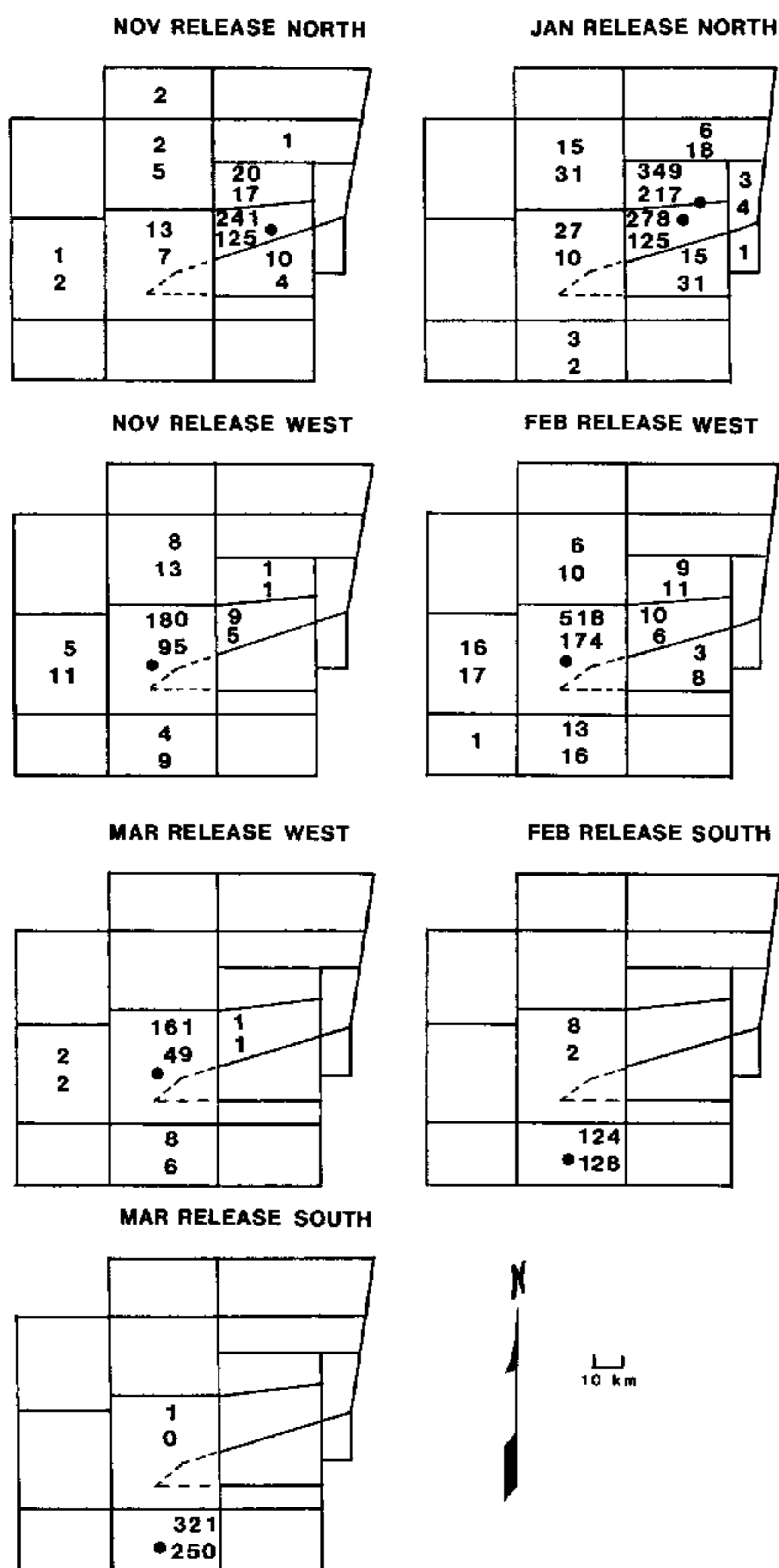


FIGURE 6.—Numbers of tagged pink shrimp returned (top number in each grid) and numbers returned per unit fishing effort (bottom number: $10^2 \times$ returns per 24-h day) from release sites outside of the Tortugas sanctuary, 1982–1983. Values represent sums of biweekly calculations from the beginning of experiments through May 31, 1983. Values for returns per unit effort were not summed when effort reported from interviews was less than 10 d/grid. Black circles represent release locations for tagged shrimp. See Figure 2 for identification of grids.

northward into the sanctuary. Costello and Allen (1966) reported apparent low-level movement of shrimp south and southwest across the Tortugas grounds from releases near Sanibel Island and Indian Key. No returns were reported from the Straits of Florida south of the grid system (Figure 3) because commercial trawlers do not operate there.

The great depth of these straits probably served as a natural barrier to migration (Costello and Allen 1966).

Reports of at least seven tagged shrimp recaptured in the sanctuary more than 3 months after release were validated by NMFS personnel. Although these shrimp may have migrated out of the sanctuary and returned prior to capture, it is possible that some shrimp remained in the sanctuary for the duration of their time at large. Costello and Allen (1966) reported a few pink shrimp remained in Barnes Sound at least 174 d after release.

Size

Length was not recorded for each tagged shrimp at the time of release because delineation of pink shrimp size distribution on the Tortugas grounds was not an objective of this study. Crude size comparisons could still be made based on total length of returned shrimp and lengths obtained from nightly samples collected during tagging operations. The data suggested that a significant percentage of tagged shrimp that were released in the sanctuary attained a length greater than 103 mm before being recaptured. No significant difference was found between recaptures taken inside and outside the sanctuary for this size category (for a detailed analysis of length distribution of pink shrimp on the Tortugas grounds, see Roberts 1986).

Sources of Error

The success of large-scale tagging studies depends on uniform cooperation from fishermen throughout all parts of the fishing grounds. The only indication of non-uniform cooperation involved illegal trawling activity within the Tortugas sanctuary. National Marine Fisheries Service personnel observed several boats trawling inside the sanctuary, although relatively little effort was reported there. It was obvious that certain shrimpers did not admit to fishing within the closed sanctuary. A portion of this effort and associated tag returns probably were reported at the perimeter of the sanctuary in grids 5 and 10, or not at all. Some shrimpers did report fishing inside the sanctuary; however, there were usually tag returns associated with these reports. Return-per-effort values determined for sanctuary grids, therefore, are questionable and the number of tag returns represents a minimum value for what was actually caught. Values of R/f for grids 5 and 10 may be only minimally affected by falsified reports, if they exist, because these areas typically have very high fishing effort.

The method used to calculate total fishing effort assumed that the distribution of the mean of effort per trip and trips per grid was approximately normal. This assumption is justified by the central limit theorem (Remington and Schork 1970), which states: "... for random samples from any underlying distribution . . . , however nonnormal it may be, the sampling distribution of \bar{x} , the sample mean for random samples of size n , is approximately normal, the approximation improving as n increases." In this study, the assumption of randomness was justified because there was no known sampling bias. An extremely large sample size exceeding 40% of the population of fishing trips lent further credence to the soundness of this methodology.

Interpretation of interview data may have affected calculations of R/f . Trip interviews frequently included descriptions of vessel trips extending from Key West to Rebecca Shoal—nearly the entire length of the fishing grounds. For purposes of calculation, fishing effort for these trips was divided equally along the length of the transect covered by the vessel. This introduced a possible error because trawling probably was not conducted uniformly along the transect. The date each vessel landed its catch was used to sort vessel trips into chronological groups to determine biweekly fishing effort. Some trips may have been sorted incorrectly due to differences between landing dates and actual trawling dates, while other trips undoubtedly overlapped time periods. These factors also may have either increased or decreased R/f values depending on the grids involved. However, the number of these anomalies was believed to be small in comparison to the total number of trips used in the analysis.

Shrimp release sites were not always located in the geographic center of grids because the grid array was not developed before initiation of field work. Only after trip interviews were received and locations of trawling activity plotted on charts could the fishing grounds be geographically subdivided sensibly. Consequently, distance from release site to adjacent grids varied in some experiments. In these cases, if two shrimp released at the same location traveled the same distance (say, 9 km) but in different directions, one individual could be recaptured inside the release grid and the other outside. This, along with non-uniform distribution of fishing effort and different but overlapping data sets, probably accounts for occasional differences between return per effort and resultant vector analyses.

Release sites in sanctuary experiments were located farther from the geographic center of the grid than those in other experiments. Sanctuary releases showed strong northward movement to the nearest adjacent grid (Figure 5). However, high R/f values also were obtained for grid 11 farther north and grid 5, the adjacent grid farthest from the release site. Thus, off-center release sites probably had little effect on overall results of the sanctuary experiments.

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